GEOMORPHOLOGY OF THE HATTAH LAKES REGION ON THE RIVER MURRAY, SOUTHEASTERN AUSTRALIA: A RECORD OF LATE QUATERNARY CLIMATE CHANGE

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KOTSONIS, A., CAMERON, K. J., BOWLER, J. M. & JOYCE, E. B., 1999:07:3t. Geomorphology of the Hattah Lakes Region on the River Murray, southeastern Australia: a record of Late Quaternary climate change. *Proceedings of the Royal Society of Victoria* 111(1): 27–42. tSSN 0035-92tt.

The Hattah Lakes series of interconnected lakes formed in a depression in the Mallee country on the River Murray. Several of these lakes lie on the floor of a pre-existing palaeo-lake, named here the Hattah Mega-Lake, which is bordered to the east by a large lunette. The rest lie on terraced floodplain sediments of the ancestral River Murray.

In this landscape three stages of fluvial, lacustrine and aeolian activity have been identified: (1) a pre-glacial stage of high river discharge and high lake water levels filling the Hattah Mega-Lake; (2) a glacial maximum stage of variable river discharge, with water levels higher than present but also encompassing periods of drought with low river levels and low water levels, and occasional drying of the mega-lake, accompanied by increased salinity, pelletal clay deflation and widespread aeolian activity; and (3) a post-glacial stage of low river discharge with vegetated floodplains, and low lake levels within smaller freshwater basin lakes.

THE geomorphology and Late Quaternary geological history of the Hattah Lakes, situated on the River Murray within the Hattah–Kulkyne National Park and Murray–Kulkyne Park, approximately 65 km south of Mildura (Fig. 1) is described in this study. They are one of the few wetland systems located on the margin of the River Murray within the semi-arid Mallee country of the western Murray Basin. In total there are about 21 lakes, all interconnected and filled by flooding of the River Murray by Chalka Creek, an anabranch that flows for approximately 18 km from its inlet to the lake system, and 26 km from the lakes back to its outlet (Fig. 2). The southern chain of lakes lie within the Hattah Lakes National Park, whereas the remainder are within the Kulkyne National Park and the Murray–Kulkyne Park along the River Murray.

The lakes are highly dependent on flooding of the River Murray, as the regional climate can be broadly classified as semi-arid with mean annual potential evaporation far exceeding median annual rainfall (Colls & Whitaker 1990). The record of river and lake levels, going back to 1908, indicates that the lake system is replenished by the River Murray once every two years, and has completely dried out only seven times between 1908 and 1964, the longest period being 24 months following the drought years 1943–45 (Robinson 1965). Observations made during the 1964 flood indicate that all the lakes had filled when water levels reached 13 feet (42.96 AHD) in Lake Hattah (Robinson 1965).

Previous investigations of the region have been directed towards hydrology and ecology. The natural water regime of the lakes has been described (Robinson 1966) and the effects of river regulation on the lake system have been discussed (Robinson 1966; Baker & Wright 1978; Shaw 1985). Robinson (1965) suggested that the lakes were the remnant of a former course of the River Murray, and recognised that their shapes were strongly influenced by wind-blown sand ridges from the west. The only geological study of the area, conducted as part of a regional hydrogeological investigation of the River Murray (Thorne et al. 1991), noted the large extent of floodplain sediments overlain by dune sands in the Hattah Lakes area, and identified a large sandy lunette with the lake-floor now occupied by the Hattah Lakes. However, the relationship between the current lake system and the former one, and between the present and past fluvial systems of the River Murray was not investigated.

This paper describes the landforms in the Hattah Lakes area, including the fluvial sequence on the floodplains of the River Murray to the east, this leading to a discussion of the evolution of the region and implications for regional climatic and environmental change.

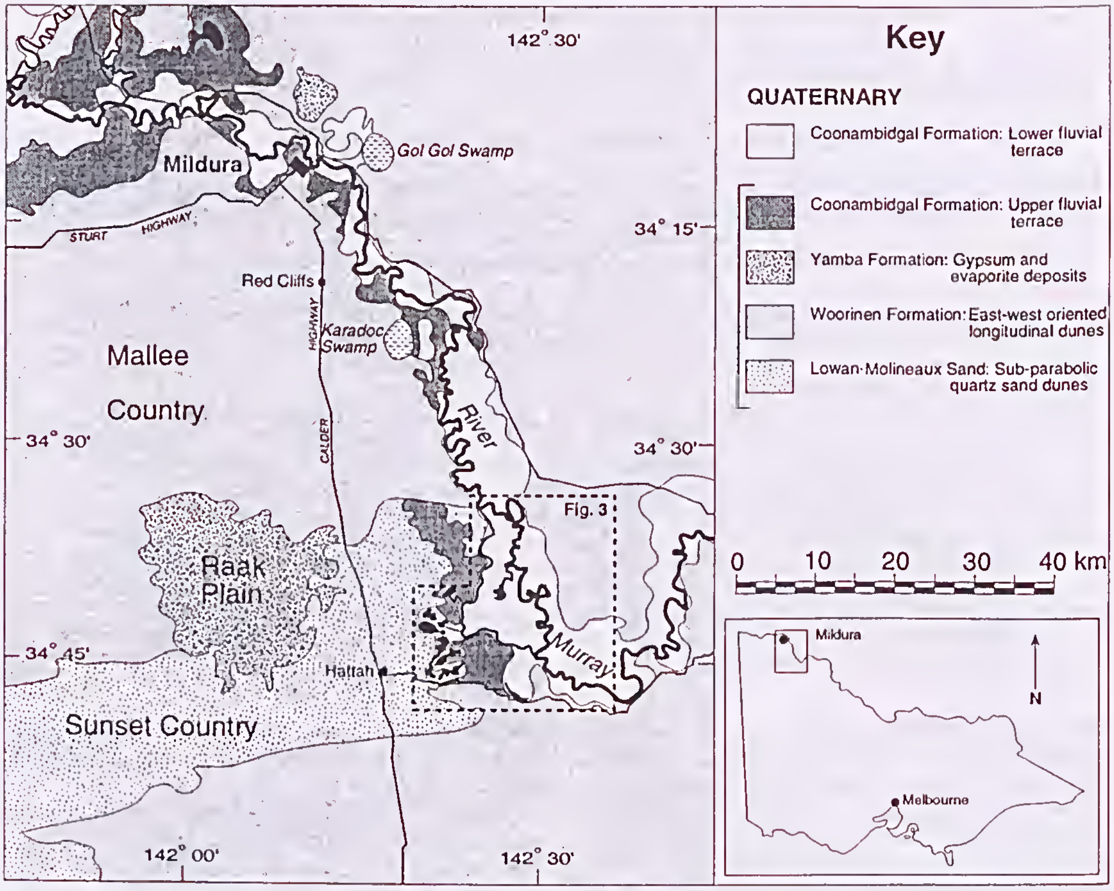


Fig. 1. Regional geology of northwestern Victoria, showing study area. Simplified after Lawrence (1972) and Lawrence & Macumber (1974).

REGIONAL SETTING OF THE HATTAH LAKES

The Hattah Lakes lie within the Mallee country of the western Murray Basin (Fig. 1). To the south the lakes are surrounded by clayey and calcareous east–west oriented longitudinal dunes of the Woorinen Formation (Lawrence 1966) that lie between 52–57 m AHD. To the north and west, and encroaching eastwards across much of the Hattah–Kulkyne National Park, are fine sandy sub-parabolic quartz dune chains of the Lowan–Molineaux Sands (Lawrence 1966) that form the easternmost limit of the Sunset Country dunefield. These dunes lie between 55–77 m AHD, and terminate on the boundary between the topographically lower-lying floodplains of the present and ancestral River Murray, which still receive periodic flooding. All the lakes lie within sandy sub-parabolic dune country, except for Lake Kramen, which lies on a floodplain terrace.

The sub-parabolic dune country occupied by the lakes is at a lower elevation than the surrounding aeolian plain, often lying 5–10 m below the level of dunes in the Sunset Country several kilometres to the west. Inter-ridge swales are often vegetated by black box, indicating periodic or occasional flooding, and dune crests carry grasses. The lakes, which lie in the lowest points, have broad areas surrounding them that are affected by water and fill during major floods (e.g. 1965 flood; Robinson 1965). Similarly, Chalka Creek often has a well defined but shallow channel surrounded by a broad area of flood-affected country.

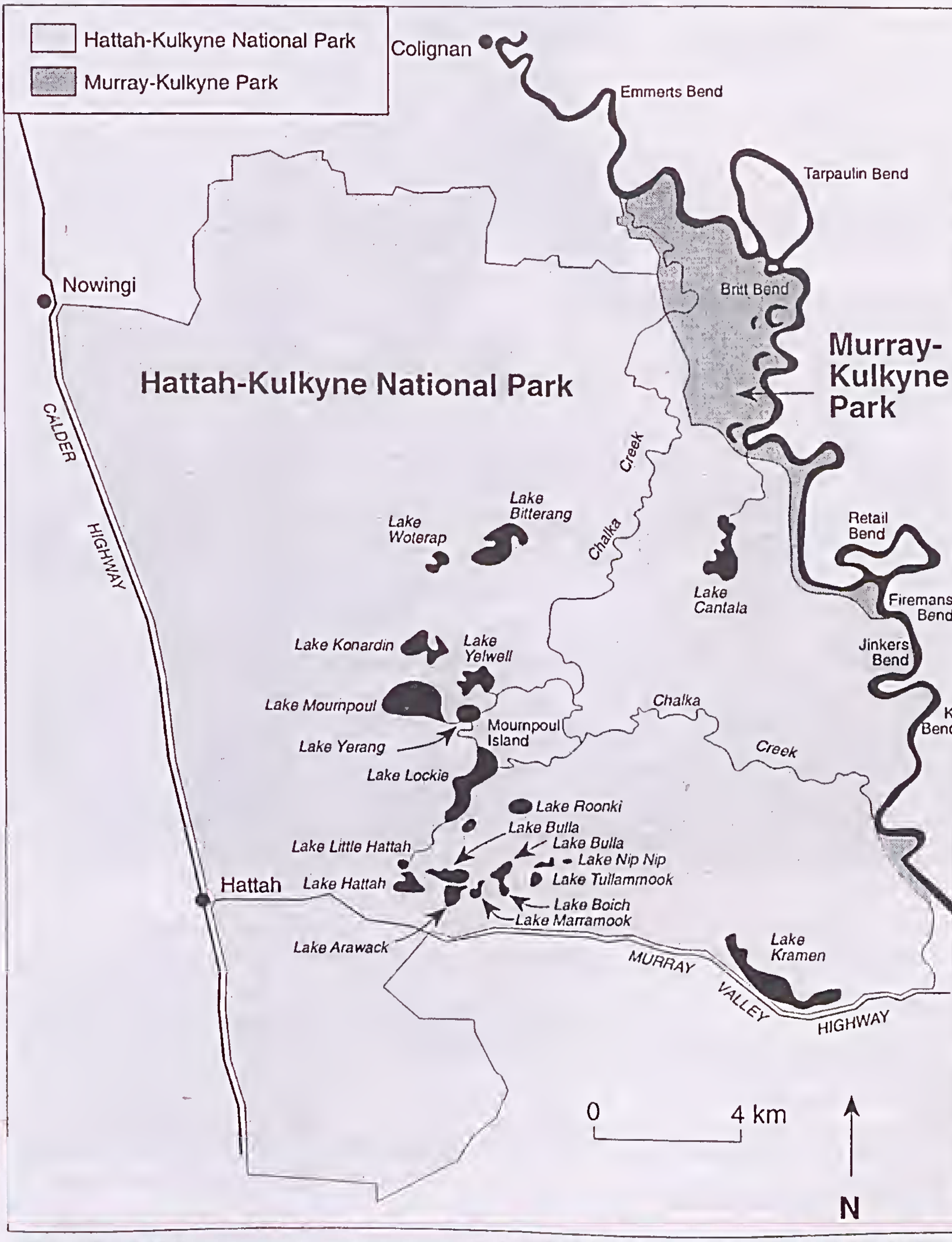
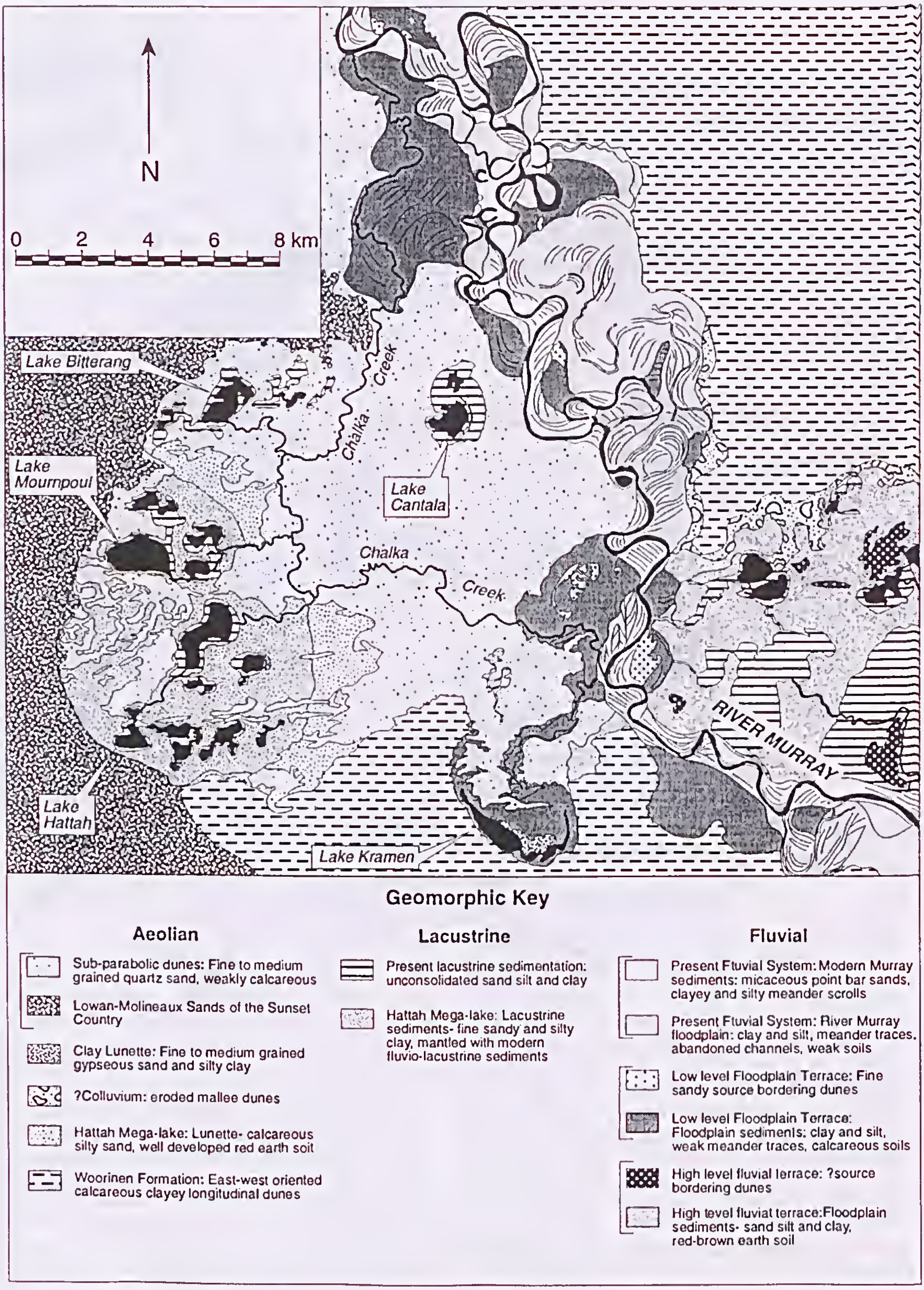


Fig. 2. Hattah–Kulkyne and Murray–Kulkyne National Parks and lakes in northwestern Victoria. Names of features mentioned in text.


N
0 2 4 6 8 km
Lake Bitterang
Lake Mournpoul
Chalka Creek
Lake Cantala
Chalka Creek
Lake Hattah
Lake Kramen
RIVER MURRAY
Geomorphic Key
Aeolian
Sub-parabolic dunes: Fine to medium grained quartz sand, weakly calcareous
Lowan-Molineaux Sands of the Sunset Country
Clay Lunette: Fine to medium grained gypseous sand and silty clay
?Colluvium: eroded mallee dunes
Hattah Mega-lake: Lunette- calcareous silty sand, well developed red earth soil
Woorinen Formation: East-west oriented calcareous clayey longitudinal dunes
Lacustrine
Present lacustrine sedimentation: unconsolidated sand silt and clay
Hattah Mega-lake: Lacustrine sediments- fine sandy and silty clay, mantled with modern fluvio-lacustrine sediments
Fluvial
Present Fluvial System: Modern Murray sediments: micaceous point bar sands, clayey and silty meander scrolls
Present Fluvial System: River Murray floodplain: clay and silt, meander traces, abandoned channels, weak soils
Low level Floodplain Terrace: Fine sandy source bordering dunes
Low level Floodplain Terrace: Floodplain sediments: clay and silt, weak meander traces, calcareous soils
High level fluvial terrace: ?source bordering dunes
High level fluvial terrace: Floodplain sediments- sand silt and clay, red-brown earth soil

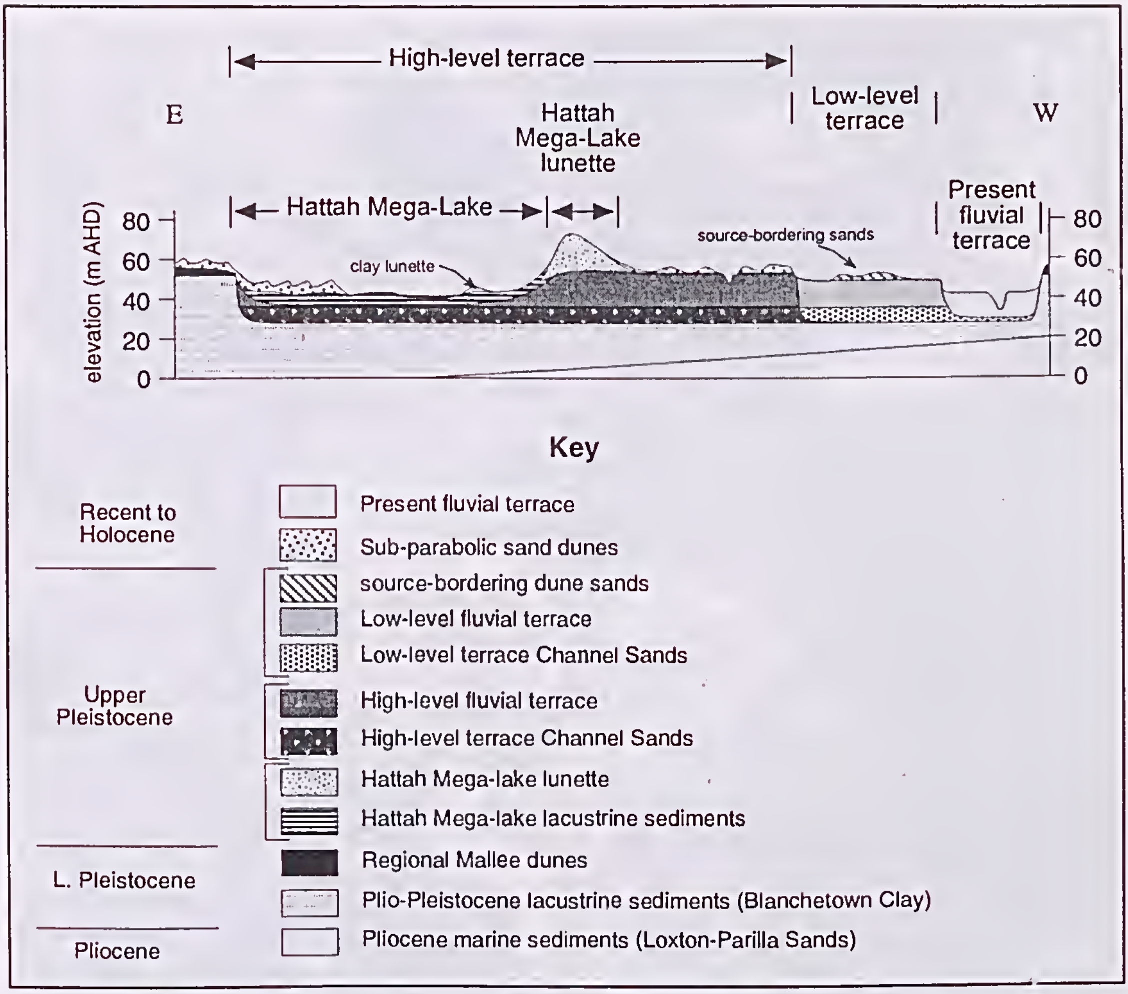


Fig. 4. Simplified east–west cross-section through the Hattah Lakes study area.

LANDFORMS OF THE HATTAH LAKES REGION

The landforms identified within the study area are mapped in Fig. 3. A simplified east–west cross-section of these features is shown in Fig. 4.

Hattah Mega-Lake

The lakes Konardin, Yelwell, Mournpoul, Yerang, Lockie, Roonki, Hattah, Bulla, Brockie, Arawak, Little Hattah, Marramook, Tullamook, Nip Nip and Boich lie on the floor of a large freshwater palaeo-lake (Fig. 3), that covers an area about 50 km^2, named the Hattah Mega-Lake (Cameron 1991). To the east the palaeo-lake is defined by a large lunette ridge approximately 10 km long and 1 km wide (Fig. 5), and to the west and south by a change in vegetation, and a subtle topographic drop from 48–56 m AHD to 43 m AHD.

Fig. 3. Geomorphic map of the Hattah Lakes and River Murray in the Hattah–Kulkyne National Park and Murray–Kulkyne Park, north-west Victoria.

Fig. 5. Aerial photograph of the Hattah Mega-Lake, showing limit of palaeo-lake and lunette ridge, and present lakes. Scale: 10 mm = 1 km.

The lunette possesses a broad rounded crest with a maximum elevation of 72 m AHD and gently dipping flanks. It is breached in its centre by the inlet and outlet channels of Chalka Creek which separate the northern and southern ends of the lunette and encircle the subdued, sub-parabolic dunes of Mournpoul Island. The southern part of the lunette is mantled by sandy dunes. The lunette is composed of well consolidated calcareous fine to medium grained sandy silt and clay, that overlies a shallow clay horizon and calcrete at depth. The lower parts of the lunette are not exposed.

Lacustrine sediments of the Hattah Mega-Lake floor lie between 40–44 m AHD and are mantled by a thin layer of modern-day fluvio-lacustrine sediments. These lacustrine sediments are currently being eroded at the western margins of present lakes, and where exposed, consist of mottled bluish-grey fine sandy and silty clay.

Present lakes and associated features within the Hattah Mega-Lake

The floor of the Hattah Mega-Lake is now occupied by a series of interconnected depressions with the present lakes occupying the topographically lowermost positions just below 40 m AHD and fed by shallow channels connected to Chalka Creek (Fig. 5). The Hattah Mega-Lake floor is vegetated with black box and river red gums that often delineate strandlines, and grow on the margins of lakes, clay pans and channels, whereas grasses predominate on dune sands. All lakes occupy broad shallow basins less than 3 m deep surrounded by thin, gently dipping organic rich, fine grained beach sands overlying dark sandy loams. The eastern sides are often bordered by a lunette.

The lakes within the Hattah Mega-Lake can be subdivided into three groups (Fig. 5): the northern group of the lakes Konardin, Mournpoul, Yerang and Yelwell; the central group consisting of the lakes Lockie and Roonki; and the southern group consisting of the lakes Little Hattah, Hattah, Bulla, Arawak, Marramook, Brockie, Boich, Tullamook and Nip Nip.

The northernmost group of lakes is separated from the central group by the lobe of sandy dunes to the south and west, and Mournpoul Island to the southeast (Fig. 5). Flood water enters the lakes through a shallow channel from Lake Lockie, and exits east of Yelwell to the Chalka Creek outlet. The arcuate nature of the northwestern edge of Mournpoul Island and the cliffed inner margin of the northern part of the Hattah Mega-Lake lunette may represent a shoreline of a former larger lake that may have existed and encompassed these lakes. The dunes of Mournpoul Island are light brown (but darker than the surrounding parabolic dunes), and quickly pass to a pale orange yellow with depth. They consist of well sorted calcareous fine quartz sand with calcareous aggregates located at about 1 m depth.

The central group of lakes is fed directly from the Chalka Creek inlet and occupy deflated depressions on the floor of the palaeo-lake. The lakes are generally surrounded by dark organic rich sandy loams vegetated with black box and red gums. Of this group of lakes only Lake Lockie has been affected in shape by eastward encroaching dunes.

The southern group of lakes is confined within dune sands that have encroached across the Hattah Mega-Lake floor and onto the lunette ridge to the east (Fig. 5). They are fed by a shallow channel that connects Lake Lockie with Lake Little Hattah, and progressively fill from west to east, with a small breach in the lunette allowing overflow of flood waters to reach Lake Kramen. Except for Lake Little Hattah, the group of lakes is separated from those to the north by a narrow tongue of sandy dunes that trends in an E–W direction. All are strongly influenced in shape by the encroaching dunes, and are separated from one another by poorly organised ridge crests oriented in a N–S direction. The lakes occupy inter-ridge depressions, with the western margin reshaped by the steep lee side of the unstable dunes, and the eastern side reworked by shoreline activity. The persistence of lakes within the inter-ridge depressions, their lobate extension oriented in an E–W direction, and the absence of any permanent lakes just north of the dunes suggests deflation of inter-ridge material.

Smaller lunettes, now vegetated with grasses, bound the eastern side of several existing lakes within, and to the north and east, of the Hattah Mega-Lake. The lunettes are typically 500–600 m in length, 100–150 m in width, and approximately 3 m in height, with an asymmetric cross-section with a steeply dipping inward slope of 6–10° and a gently dipping lee slope between 1–3°. Where the sediments of the lunette are exposed, dark brown loams are characteristic, with moderately sorted fine to medium grained sand and silt-sized clay pellets with occasional Wüstenquartz (silt-sized aeolian quartz dust with a thin coating or argillan of clay and ferric cement; Radczewski 1939) overlain by chernozem soils with fine disseminated carbonate accumulation. At a depth of about 2.4 m secondary precipitates of lenticular gypsum crystals less than 1 mm in size are common.

The crests of the lunettes contain shell middens composed of fragments of freshwater bivalves and occasional shards of animal bone that are probably Aboriginal in origin. The shells, harvested from the lakes, indicate the return of freshwater conditions to the lakes after clay lunette building had ceased.

The dunes that overlie the southern half of the Hattah Mega-Lake lunette are reddish brown throughout. The pigmentation is due to ferri-argillans (see Stace et al. 1968) with irregular thickness, indicating transport of the sediment after cutan development. The absence of similar dunes on the northern section of the lunette indicates that there was no eastward movement of sand across the lake, and may suggest that the north part of the lake may have contained water during this time of dune mobility (Cameron 1991).

The dunes which extend across the lake floor of the Hattah Mega-Lake are preserved as elevated mounds of pale reddish-brown sand that have been reshaped by flood waters. They are pale orange, fine to medium grained, with weakly developed 20 cm thick nodular calcareous horizons often exposed in the base of blowouts at a depth of 4 m. The intensity of pigmentation in these dunes decreases with depth.

Floodplains and terraces of the River Murray

The fluvial sediments of the River Murray and its anabranches form the uppermost sequence of the Late Pliocene to Recent Shepparton Formation (Lawrence 1966) and Late Pleistocene to Holocene Coonambidgal Formation (Butler 1958, 1961). Within the study area, these can be subdivided into three major groups based on morphology, relative topographic position and pedogenesis (Fig. 3; Table 1) (Kotsonis 1991).

High-level floodplain terrace. Topographically high level exposures of fluvial sediments mantled by eastward encroaching sub-parabolic dunes (similar to those described within the Hattah Mega-Lake) occur on the western bank of the River Murray between Jinkers Bend and north-east of Retail Bend (Fig. 2). The elevation of the high level floodplain is similar to the sub-parabolic dune country east of the Hattah Mega-Lake.

Meander scrolls and traces are obscured by dune cover, which masks the westward extent of the floodplain. However, dark heavy clays underlie the dunes and outcrop along the banks of Chalka Creek, and extend toward the eastern margin of the Hattah Mega-Lake. These clays lie on a topographic level similar to exposures along the River Murray, and may represent possible floodplain sediments of the high level terrace. They probably underlie lakes Cantala, Bitterang and Woterap, which require an impermeable base to prevent significant loss of surface water through infiltration. The growth of black box vegetation within inter-dune swales in these areas also suggests water is retained in the near-surface environment even when the surface may be dry.

Exposures along the banks of the River Murray comprise basal ferruginised and cross bedded fine to coarse quartz sandstone, part of the Channel Sands aquifer system (Thorne et al. 1991), overlain by laminated abandoned channel clays and floodplain clays. Individual overbank clay units are thick (>1 m), and typically micaceous. Upper surfaces of channel clays are weathered with red brown mottling, and heavily impregnated with multiple generations of carbonate rhizomes. Solonised brown soils with massive rhizomorph-rich and fine grained nodular carbonate characterise the upper surface of the terrace. The A horizon is absent, probably removed during mobilisation of the overlying dune sands.

	High level terrace	Low level terrace	Present fluvial system
Vegetation	Mallee type	Black box and red gum	Red gum and black box
Meander geometry	Large	Large	Small
Meander wavelength			
Chalka Creek	950–1125 m	300–600 m	175–325 m
River traces	Not visible	2250–2375 m	1225–1800 m
Elevation above present			
Murray River banks	8–10 m	2–4 m	0–2 m
Soil profile	Calcareous solonised brown soils	Calcareous chernozems	Siliceous sands and alluvial soils

Table 1. Summary of the dominant characteristics of the fluvial systems.

Low-level floodplain terrace. Lying 2–4 m below the high level terrace is a low-lying floodplain terrace with a smooth and regular upper surface consisting of dark grey to pale grey-brown cracking clays. Only isolated patches of this terrace remain, onlapping older terraced deposits or the surrounding mallee dune country, or forming elevated benches within lower-lying floodplain sediments of the present river system (Fig. 3). The upper surface is characterised by weak meander traces highlighted by black box vegetation and occasional sandy source bordering dunes.

The boundary between the high level terrace and the low level terrace on the western side of the River Murray is masked by eastward encroaching fine red dune sands. Lake Kramen is located upon dark grey-brown cracking clays of the low level terrace, excavated in a large arcuate abandoned channel in the surrounding Mallee (Fig. 6) and underlain by Channel Sands (Thorne et al. 1991). The area occupied by the lake is mantled by sub-parabolic fine sandy dunes with inter-dune swales reworked by flood waters. The lake lies at the terminus of the depression, and is fed directly from the River Murray, overflow of the Chalka Creek inlet during flooding, and from overflow from the Hattah Mega-Lake. A poorly defined sandy lunette on the eastern side of the lake is probably derived from reworked dune sands.

Source-bordering dunes on the terrace occur on the inner (eastern) side of meanders (Fig. 6). They are typically subdued features that rise 1–2 m above the level of the floodplain, and consist of fine uniform red sand that is significantly paler than the dunes that overlie the high level terrace. These dunes are now vegetated with grasses.

Exposures along banks of the River Murray consist of partly ferruginised and cemented micaceous sandstone, part of the Channel Sands aquifer system (Thorne et al. 1991), overlain by laminated floodplain clays. The sands show well preserved cross bedding and ripple marks with fining upwards sequences. The overlying micaceous laminated floodplain clays are thick (≤1 m). Weakly mottled or carbonate rhizomorph-rich upper surfaces occur in many areas, but not as prominently as on the high level terrace. The rhizomorphs occur in irregular columns and can reach lengths of over 30 cm and thicknesses up to 5 cm, with two generations of rhizomorph-rich layers sometimes found in the upper parts of the overbank clays. The upper surface is characterised by a weakly developed calcareous soils (calcareous chernozems) with fine disseminated carbonate in the B horizon.

Present floodplain. The present and active floodplain of the River Murray is entrenched and incised within older terraced deposits and occupies the lowest topographic position in the landscape. It is vegetated with river red gum and black box woodland that highlights meander scrolls and abandoned channels. The present floodplain can be subdivided into the sediments of the modern River Murray, and its meander belt (Figs 3, 6). Immature and non-calcareous uniform soil profiles are typical of the floodplain.

The meander belt of the present River Murray lies approximately 1 m below the low level terrace. To the south, it is confined within a narrow belt near the river, but centrally and to the north the floodplain diverges to the east and covers a belt over 4 km wide. The upper surface, typically organic rich with dark friable clays and cracking clays, is slightly undulating with well preserved meander scrolls and abandoned channels. Bank exposures consist of pale red weakly consolidated micaceous quartz sands overlain by weakly laminated mottled pale brown-red sandy clays. Soils are predominantly uniform medium-textured siliceous loams that grade with depth to mottled friable sandy overbank clays.

The modern sediments of the River Murray lie less than a metre below the level of the meander belt and consist of dark brown-red friable and cracking floodplain clays. The upper surface is uneven with well preserved meander scrolls. Micaceous point bar sands are commonly found on the inner margins of meanders. Soils consist of siliceous sands and alluvial soils.

MEANDER WAVELENGTHS OF TERRACES

Measurements of meander wavelength (sinuosity) derived from traces of river migration on the upper surface of the floodplains can record information concerning palaeo-river flow. Meander wavelength measurements are presented in Table 1.

Meander scrolls are observed on all the terraces except for the high level terrace which is mantled by dunes. However, the distinct change in meander size of the Chalka Creek channel as it traverses the high and low level terraces suggests that it may have developed on an abandoned channel that connected the Hattah Mega-Lake with the river (Fig. 6). Measurements of the meander wavelength of Chalka Creek on the high level terrace vary between 950 to 1125 m, compared to values of 300 to 600 m on the low level terrace. Similarly, the width of the Chalka Creek channel is larger (15 m on the high level terrace compared to 7 m on the low level terrace). The wavelengths of meander scrolls on the low level terrace are between 2250 to 2375 m.

The meander wavelengths of scrolls and abandoned channels, including oxbow lakes, of the present River Murray and its floodplain are

Fig. 6. Aerial photograph of Lake Kramen and Chalka Creek inlet. Note position of Lake Kramen on the abandoned meander of low level terrace, and change in meander geometry of Chalka Creek as it traverses the high level and low level terrace. Scale: 10 mm = 1 km.

smaller as compared to those of the older terraces, with meander wavelengths between 1200 and 1800 m. The larger meander wavelengths of the present system are also observed on Chalka Creek, with younger superimposed meanders between 175 to 325 m in wavelength.

DISCUSSION: GEOMORPHIC SEQUENCE AND CHRONOLOGY

The changes in morphology, pedogenesis and sediment type permit the construction of a geomorphic and relative chronologic sequence for the Hattah Mega-Lake and the fluvial terraces within the study area. The sequence can be correlated with other Late Quaternary events and landforms across the Murray Basin and southeastern Australia (Stephens 1991; Joyce et al. 1991). Evidence for the fossil nature of landforms is confirmed by the development of soils and the presence of vegetation. The inferred chronology of landform evolution is presented in Table 2.

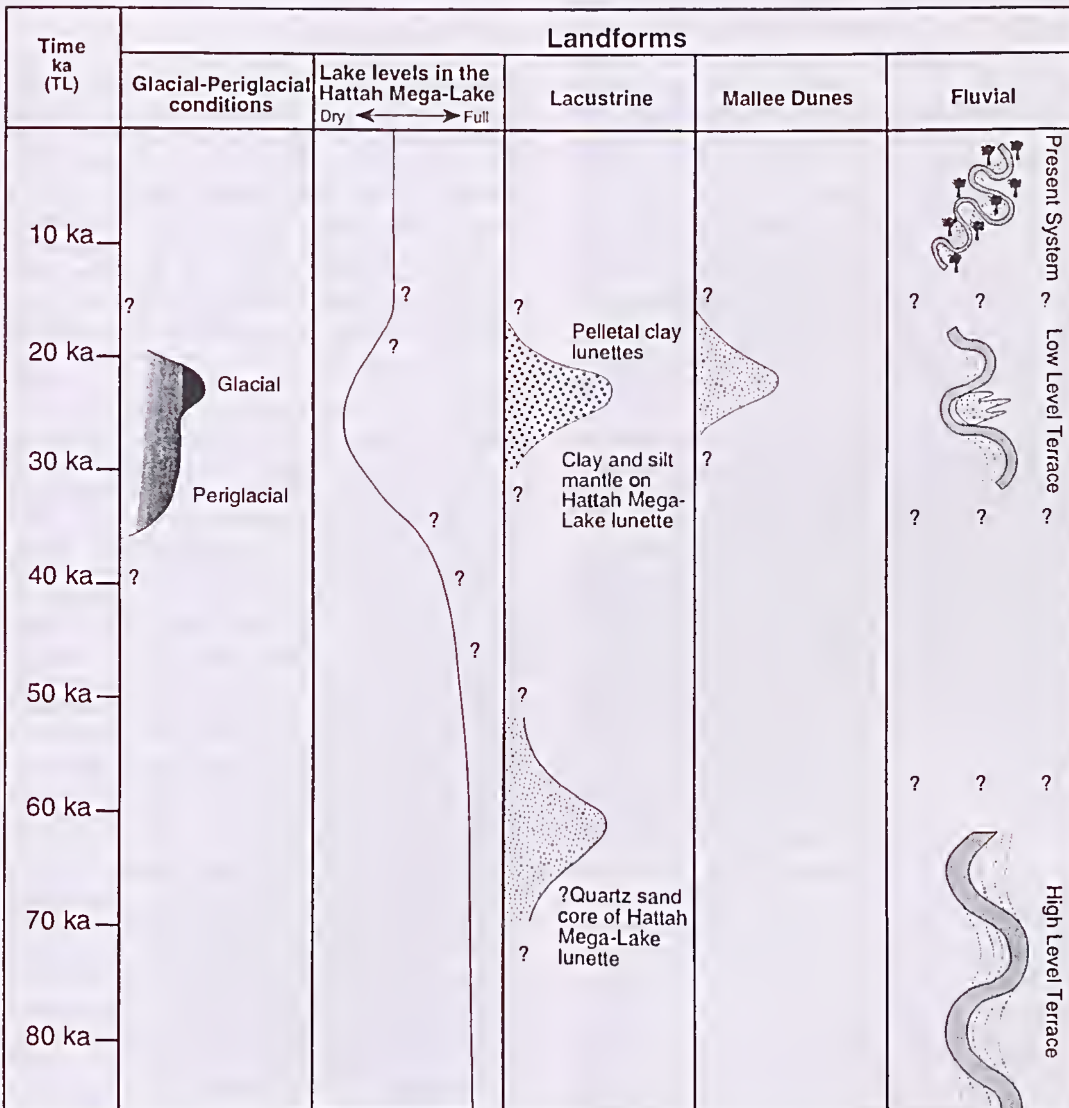


Table 2. Inferred chronology of landform evolution in the Hattah Lakes and River Murray over the last glacial cycle (after Page et al. 1994, 1996; Page & Nanson 1996).

Fluvial systems

The fluvial terraces identified here correspond morphologically to the ancestral river systems described elsewhere for the Murray Basin (Pels 1964a, 1966). The high level terrace is part of the Shepparton Formation (Butler 1958; Lawrence 1966, 1975), and is equivalent to the Rufus Formation of Gill (1973) and Neds Corner Land System of Rowan & Downes (1963), but may be significantly older than the pre-glacial Green Gully/Tallygaroopna sediments at Echuca (Bowler 1978) and Ancestral River I of Pels (1964a) based on the development of well differentiated red earth (duplex) soil profiles with multiple generations of soil carbonate. However, thermoluminescence dating (abbreviated TL) of the Green Gully terrace near Echuca yielded ages between 100 to 65 Ka (Page et al. 1996), and corresponds to the Coleambally phase of fluvial activity on the Riverine Plain (Page and Nanson 1996; Page et al. 1996). This fluvial system may also correspond to the younger Kerarbury or Gum Creek phases, based on pedogenesis and morphology, and TL dated at 55–35 Ka and 35–25 Ka respectively. The high level terrace may be of greater antiquity than that suggested previously by radiocarbon dating.

Traces of original channel morphology preserved as meander scrolls and oxbow lakes on the high level terrace are hidden beneath dune cover. However, meander wavelength and channel size observed along the length of Chalka Creek as it traverses the different terraces (Table 1) suggests that it inherited original channel morphology. The geometry and size of the creek on the high level terrace is significantly larger than the present fluvial regime, suggesting higher river discharge. As a comparison, the channel size of Chalka Creek on the terrace is over three times larger than those observed on the present floodplain.

The low level terrace and the floodplain and sediments of the present River Murray are part of the Coonambidgal Formation (Butler 1958, 1961; Lawrence 1966), as defined by the characteristic grey soils developed on them. Based on the similarity in pedogenesis and morphology, the low level terrace is equivalent to the Coonambidgal II unit of Pels (1964a) and Bowler's (1978) Kotupna Phase fluvial sediments radiocarbon dated at 25 000–30 000 to 15 000 years BP near Echuca. TL dating of the Kotupna channel has yielded similar dates, but slightly older at 34 Ka (Page et al. 1991), and has been correlated to the Yanco Phase of fluvial activity dated at between 20–13 Ka (Page & Nanson 1996; Page et al. 1996).

The sediments of the present River Murray and meander belt form the final episode of fluvial deposition with abandoned channels and point bar traces with dimensions similar to those of the modern Murray. This fluvial system is present along the length of the River Murray and its tributaries, and corresponds to the Goulburn–Murray Phase sediments described at Echuca that developed after about 15 000 years BP (radiocarbon dated; Bowler 1978).

Lakes and lunettes

Hattah Mega-Lake. The entrenchment of the Hattah Mega-Lake below the level of the surrounding Mallee Country on an elevation coincident with the high level terrace indicates that the palaeo-lake developed within the Murray Trench and on fluvial sediments, and is consistent with evidence of possible high level terrace deposits extending towards the eastern margin of the lake. The calcareous soil developed on the Hattah Mega-Lake lunette shows strong pedogenic differentiation with calcrete similar to that described elsewhere in southeastern Australia which dates between 24 000 to 36 000 years BP and older (Bowler 1976; Bowler & Polach 1971; Pels 1964b), suggesting that the palaeo-lake may be of equivalent age. TL dating of the outer lunette of Lake Urana with similar pedogenic differentiation yielded 55–35 Ka (Page et al. 1994). Assuming the Hattah Mega-Lake is of similar TL age to the outer lunette of Lake Urana (55–35 Ka), then the high level terrace must correspond to the Coleambally Phase (100–65 Ka) of fluvial activity and not the younger Kerarbury (55–35 Ka) or Gum Creek phases (35–25 Ka). The large size of the palaeo-lake, combined with evidence of high river discharge on the River Murray, suggests that it contained freshwater.

The Hattah Mega-Lake probably developed on an old meander cut-off on the upper surface of the high level terrace, forming an oxbow lake that was continually fed with flood waters from the River Murray. Continual inflow of water could create a permanent freshwater body from which lakeshore drift could provide sediment for a beach and associated lunette to develop. The lake was probably fed through the wide gap that separates the northern and southern sections of the lunette by the Chalka Creek inlet and outlet channels and now occupied by Mournpoul Island (Fig. 5), similar to the deltaic channel system and gravel fan of Madowla Park Lagoon that fed Lake Kanyapella at Echuca (Bowler 1978).

Clay lunettes. The weak pedogenic differentiation of the clay rich lunettes combined with their superimposition within the Hattah Mega-Lake indicate that they post-date the development and drying of the palaeo-lake. The presence of salts and gypsum within these lunettes, and the secondary precipitates deeper within the soil profile indicates deposition of these features during conditions of high salinity, which could only be achieved if shallow saline groundwaters, now at 38 m AHD (Thorne et al. 1991) could intercept the landsurface. The conditions required for clay lunette building have been described, where seasonal lowering of saline groundwater tables below the lake floor cause efflorescence of clays and the formation of sand and silt-sized pelletal aggregates that are deflated by prevailing easterly winds (Bowler 1971, 1983; Bowler & Wasson 1984). The exposed upper parts of the Hattah Mega-Lake lunette that comprise silt and clay may record the initial phase of pelletal clay deflation from the lake floor as the lake began to dry.

The presence of Wüstenquartz associated with the pelletal clay indicates widespread aeolian mobilisation synchronous with lunette formation.

Dunes. The similarity in pedogenic differentiation of the various dune forms, with weak calcareous segregations and clay organisation (sandy dunes, dunes of Mournpoul Island, clay lunettes, and soils of the low level terrace with source bordering dunes) suggests regional and contemporaneous aeolian activity. The complete mantle of dunes on the high level terrace, combined with the partial mantle on the Hattah Mega-Lake floor and lunette indicates that dune encroachment proceeded after the drying of the palaeo-lake, and therefore post-dates the terrace. This is supported by the truncation and erosion of the soil developed on the high level terrace by the overlying dunes.

The association of source bordering dunes and the partial encroachment of sandy dunes on the low level terrace (Kotupna Phase; Yanco Phase) suggests aeolian mobility climaxed during deposition of the terrace. Although localised deflation is now occurring in the Mallee as a consequence of European agricultural practices and the clearing of native vegetation, the process of aeolian mobilisation can be described as fossil. However, it is important to note the association between the absence of vegetation and aeolian activity, as widespread dune mobility can be facilitated only by the removal of vegetation, which would expose the landsurface to high velocity winds (Bowler 1978).

The absence of source bordering dunes and the truncation of sandy dunes on older terraces by the present fluvial regime (Goulburn–Murray Phase) indicates that dune mobility had ceased when this fluvial system became active at about 15 000 years BP. Within the Hattah Mega-Lake, the termination of aeolian activity is recorded by the change from saline water in lakes and pelletal clay lunette formation to the return of freshwater conditions as recorded by the harvesting of freshwater fauna from the lakes by the local Aborigines.

THE CLIMATIC SEQUENCE

The landforms of the Hattah Lakes and River Murray floodplains record the history of climatic change that can be quantified here only in relative terms of 'wetter' or 'drier' conditions that encompass the balance between precipitation and evaporation that prevailed regionally across south-eastern Australia. These changes in climate have regional consequences in terms of vegetation and the stability of landforms. Changes in discharge on the River Murray can be related to events at higher altitudes in the southeastern highlands, where glacial and periglacial conditions affected runoff and sediment supply to the Murray Basin plains.

The existence of the Hattah Mega-Lake and lunette, assumed at before 35–55 Ka, indicates a period of significantly higher surface water levels in the Murray Basin, and/or wetter climates with higher precipitation/evaporation ratios than today. High discharge along the River Murray is evidenced by the large meander patterns of Chalka Creek preserved on high level terrace. Assuming water levels in the Hattah Mega-Lake between 45–50 m AHD (water depth between 3–7 m) during this period of lake full conditions, the flood levels on the River Murray required to fill the palaeo-lake need to be several metres above the maximum flows that have been recorded since 1908 (see Bibra & Mason 1967). For example, flood levels 2–7 m above those of the 1964 flood would be required to fill the lake to capacity (the 1964 flood reached only 42.96 AHD), and for comparison, the palaeo-lake would have partially filled during the 1956 flood where water levels in Lake Hattah reached 45.10 m AHD. However, sustaining standing water in the Hattah Mega-Lake under present climatic conditions (present precipitation/evaporation ratio), flood levels of the above magnitude would be required at least once every two years (Bureau of Meteorology Climatic Atlas of Australia 1975).

The Hattah Mega-Lake is assumed to have begun to dry between 35–25 Ka. This period represents the transition between lake-full conditions and high river discharge of the high level terrace, to pelletal clay lunette development and deposition of the low level terrace. Within the Hattah Mega-Lake, this is recorded as segmentation of the palaeo-lake into several smaller lakes, either as a consequence of reduced river flow along the River Murray, or a higher evaporation/precipitation ratio.

Widespread dune activity in the surrounding Mallee Country, within the Hattah Mega-Lake, and on the fluvial terraces began between radiocarbon dates 28 000 to 22 000 years BP (Bowler in Magee & Beaton 1985; Readhead 1988) and TL dates 25–20 Ka (Page et al. 1996) with the appearance of glacial and periglacial conditions in the highlands of southeastern Australia. The loss of vegetation from the plains implies a climatic change which was adverse to the growth of eucalypt and red gum woodland, probably as a result of winters with severe cold and frost, which are detrimental to eucalypt cover (Bowler 1978). The presence of desert-derived dust (Wüstenquartz) indicates climates with intensified seasonality, with hot dry summers producing drought conditions in the continental interior. The loss of woodland vegetation from the floodplains would have facilitated dune growth from exposed point bars during times of low flow. Incidentally, the large meander patterns of the low level terrace (Kotupna Phase sediments) indicate higher river flow than today, probably as a consequence of the reduced vegetation cover and higher runoff in the catchment areas further upstream, along the Murray's anabranches, and in the Southeastern Highlands.

Within the Hattah Mega-Lake, high regional groundwater tables, probably inherited from the past wet phase, combined with the loss of vegetation and increased water infiltration, contributed to the rise in saline groundwaters and salinisation of the palaeo-lake. This process was accelerated by the concentration of salts from drying of the lake under arid conditions (reduced precipitation), resulting in clay efflorescence and the building of pelletal clay lunettes.

The development of the reduced flow and narrow channels of the present fluvial regime (Goulburn–Murray Phase) at about 15 000 years BP marks the cessation of dune building and the return of vegetation to the Mallee plains and the floodplains. This coincides with the disappearance of glacial and periglacial conditions in the southeastern highlands (Bowler et al. 1976) and the return of woodland vegetation to the catchment areas of rivers, resulting in reduced runoff reaching the Murray Basin plains. This may coincide with the return of freshwater conditions in the Hattah Lakes, which may also extend beyond this time to between 20–13 Ka (Page et al. 1994, 1996). The extension of woodlands is dated at between 13 000 and 10 000 years BP (Raine 1974; Dodson 1974, 1975), and marks the change to climates with higher temperatures and decreased seasonal stresses (Bowler 1978) that promoted the growth of vegetation.

The similarity in morphology between the floodplain system that developed throughout the Holocene (Goulburn–Murray Phase) and the present River Murray suggests moderate climates, comparable to those of today, have persisted since the end of the last glacial cycle. Within the Hattah Mega-Lake pelletal clay deflation ceased as groundwater tables fell below the capillary zone, probably as a consequence of reduced infiltration caused by the return of vegetation to the landscape. The return of permanent vegetation, the growth of eucalypt and mallee scrub in the Mallee and red gum and black box woodland on the floodplains, provided stability to the landscape that prevented significant dune activity during times of severe drought.

SUMMARY AND CONCLUSIONS

The Hattah Lakes within the Hattah–Kulkyne National Park are a group of lakes that developed on the exposed lake floor of a once much larger lake, named the Hattah Mega-Lake. The history of the paleo-lake during the Late Quaternary can be correlated with the record of fluvial sedimentation on the River Murray nearby, and reflects the influence of regional climatic change associated with the last Glacial Cycle. Evidence presented here indicates higher discharge on the River Murray and high lake levels before 35 Ka, when moist conditions prevailed. However, during the Glacial Maximum there was variable river discharge, probably as a consequence of alternating summer drought and higher winter runoff in catchment areas further upstream, and facilitated by the loss of local and regional vegetation. Although discharge during glacial times may have been lower than during pre-glacial times, the loss of vegetation in highland areas and within the study area increased runoff resulting in a greater impact on the landscape. Post-glacial times are characterised by the return of vegetation and landscape stability, with the return of woodland vegetation in catchment areas further upstream significantly reducing runoff to the Murray Basin.

The Hattah Mega-Lake may have formed on an old meander cut-off sometime before the last Glacial Cycle, probably before 35 Ka. The development of the lake and lunette reflects wetter climates than that of today and higher discharge on the River Murray. With the onset of arid conditions associated with the last Glacial Cycle, the Hattah Mega-Lake began to dry, accompanied by the loss of vegetation and widespread dune activation. Numerous smaller deflationary basins developed on the lake floor, and increased salinity caused pelletal clay lunettes to develop. To the east, the River Murray incised within the older terrace and developed a lower lying aggradational floodplain. The disappearance of glacial and peri-glacial conditions in the highlands heralded the return to more moderate temperatures that promoted the growth of vegetation that stabilised the land-scape. The growth of mallee eucalypts on the dunes hindered significant dune mobilisation, whereas the return of river red gums and black box vegetation to the floodplains caused a reduction in bank erosion and the incision of the present river system within older fluvial sediments. Deflation ceased within the Hattah Mega-Lake as falling ground-water promoted the return of woodland vegetation and freshwater conditions within smaller lake basins.

ACKNOWLEDGEMENTS

The authors wish to thank the Museum of Victoria for providing financial support towards the conduct of the initial research (Museum of Victoria Research Grants). The Rural Water Corporation is acknowledged for access to aerial photography and R. Thorne is thanked for his fruitful discussions and comments. The Victorian Department of Conservation and Environment is acknowledged for its approval of research permits for study of the Hattah–Kulkyne National Park and the Murray–Kulkyne Park. Finally, the assistance of the park rangers is also acknowledged.

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